

**ATTENUATION OF ELECTROMAGNETIC ACOUSTIC NOISE FROM A
VARIABLE SPEED INDUCTION MOTOR BY USING DYNAMIC
VIBRATION ABSORBER**

by

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**Thesis submitted in fulfillment of the requirements
for the degree of
Master of Science**

March 2016

ACKNOWLEDGEMENTS

A million thanks to Prof. Zaidi bin Mohd. Ripin for supervising me for my Masters degree. Without his guidance this thesis will not be possible. I remember the times that I was lost and clueless in my research direction. Your guidance support made me on track again and to finally able to complete my research successfully. Apart from your technical advice, I am also grateful for all the life lessons and philosophical aphorisms that you have shared with me.

Thanks to Prof. Horizon Walker Gitano-Briggs for inspiring my curiosity and motivating me to continue my studies. Thanks to technicians Mr. Wan Amri, Mr. Baharom Awang , Mr. Zalmi Yop, Mr. Ahmad Shauki, Mr. Jamaluddin Che Mat and also Mr. Nazir for their technical assistance. Thanks to USM office staff Pn. Farah Hamid, Pn. Wan Zahida, Pn.Bayzura and Pn.Afzan for managing my candidature matters. Many thanks to Dr. Najib Ab. Hamid and Dr. Tan Yeow Chong who have assisted me when I first came to Vibration Lab. Thanks to Dr. Devarajan Ramasamy, Dr. Ooi Lu Ean, Dr. Teoh Choe Yung, Dr. Chuah Han Guan, Dr. Tan Wei Hong, Teoh Yew Heng, Khoo Aik Soon, Lee Jih Houh, Goh Chin Yuan, Cham Chin Long, Lee Ying Wei, Chan Ping Yi, Wong Chee Koon, Syazli, Zhafran, Rabani, Izuddin, Sahlan, Farhana, Umami, Mas and CC Leong for their friendship.

To my parents, Mr. Radha Valliappan and Raja Rajeswari thanks for bringing up and nurturing me. Thanks to my aunt, Ms. Boovaneswari Govindasamy who had supported my education for as long as I can remember. Finally, I would like to express my deepest gratitude to my beloved sister Ms. Kodieswary Radha who had provided me moral and financial support throughout my Masters degree at USM.

TABLE OF CONTENTS

Acknowledgements	ii
Table of Contents	iii
List of Tables	vi
List of Figures	vii
List of Abbreviations	xiv
List of Symbols	xv
Abstrak	xvi
Abstract	xvii

CHAPTER 1 - INTRODUCTION

1.1 Overview	1
1.2 Problem Statement	5
1.3 Motivation	5
1.4 Objective	6
1.5 Contributions	6
1.6 Scope	7
1.7 Outline	7

CHAPTER 2 - LITERATURE REVIEW

2.1 Overview	8
2.2 Noise Generation Mechanism	8
2.3 Electromagnetic Noise Attenuation Method	10
2.3.1 Electromechanical Design	10
2.3.2 Pulse Width Modulation (PWM) Strategy	13
2.3.3 Other Methods	16
2.4 Dynamic Vibration Absorber	17
2.4.1 Theory	17
2.4.2 DVA Application Examples	21

2.5 Summary	25
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CHAPTER 3- METHODOLOGY

3.1 Overview	27
3.2 Induction Motor and Inverter Specifications	27
3.3 PWM Waveform Tracing.....	29
3.4 Noise and Vibration Characterization	30
3.4.1 Spectral Test.....	31
3.4.2 Experimental Modal Analysis (EMA)	33
3.4.3 Operational Deflection Shape (ODS) Analysis.....	35
3.4.4 DVA Experimental Modal Analysis	37
3.4.5 Motor FRF Validation.....	39
3.5 DVA Implementation	41
3.5.1 Effectiveness at location A, B, C and D.....	41
3.5.2 DVA Vibration Correlation.....	43
3.5.3 Sound Pressure Level Correlation.....	44
3.5.4 Effectiveness at Variable Speed.....	46
3.6 Section summary	47

CHAPTER 4 - RESULTS AND DISCUSSIONS

4.1 Overview	48
4.2 Characterization results	48
4.2.1 Spectra Comparison	48
4.2.2 Natural Frequency and Mode Shapes	58
4.2.3 Operational Deflection Shape Animation	62
4.2.4 DVA Characterization.....	64
4.3 DVA Implementation	66
4.3.1 General DVA Implementation	66
4.3.2 Motor FRF Validation.....	69
4.3.3 Vibration reduction at X, Y, Z and R axis	71
4.3.4 Vibration reduction at B,C and D locations	74
4.3.5 Surface Vibration and DVA Vibration Correlation	77
4.3.6 Sound Pressure Level and Surface Vibration Correlation	80

4.3.7 Effectiveness at Variable Speed.....	83
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CHAPTER 5 - CONCLUSION AND FURTHER WORKS

5.1 Conclusions	86
-----------------------	----

5.2 Further Works	87
-------------------------	----

References.....	88
-----------------	----

List of Publications

LIST OF TABLES

	Page
Table 1.1 Various types and source of acoustic noise from a variable speed induction motor (Gieras et al., 2005)	2
Table 3.1 Specifications of Induction Motor	29
Table 3.2 Specifications of Inverter	29
Table 4.1 Modes and natural frequency of motor structure	59
Table 4.2 Classification of acceleration magnitude of 80 points on motor surface at 6 kHz and speed of 0 rpm	63
Table 4.3 List of natural frequencies for DVA sample bolts	66
Table 4.4 Changes on the 6 kHz frequency component of the surface vibration spectrum for different lengths of bolt samples	69
Table 4.5 Surface vibration reduction percentage on all four locations at different axis	75
Table 4.6 Comparison of decrease in motor surface vibration and increase in DVA vibration	80
Table 4.7 Sound pressure level reduction at location X1, X2 and R1 upon DVA attachment	82
Table 4.8 Summary of surface vibration reduction at various motor speeds	83

LIST OF FIGURES

		Page
Figure 1.1	Exploded view of an induction motor. (1-Front end shield, 2 - Bearing, 3 – Cage rotor, 4 - Stator, 5 – Housing, 6 – Rear end shield 7- Cooling Fan, 8- Fan Cowl) (Wildi, 2002)	1
Figure 1.2	Maximum permissible Sound Power Levels in Decibels for IEC Squirrel Cage Induction motors (Toliat and Kliman, 2004)	4
Figure 2.1	Radial Maxwell magnetic force (F_R) and tangential magnetic force (F_T) in the air gap. (Pyrhönen et al., 2008)	8
Figure 2.2	Mechanism for electromagnetic noise generation in induction motor (Gieras et al., 2005)	9
Figure 2.3	Image of (a) Unskewed rotor (b) Skewed rotor (Kubicek et al., 2009)	12
Figure 2.4	Figure 2.4 (a) Typical PWM is generated from comparison of sine wave and triangular wave (Kükrer, 2000) (b) Comparison of harmonics spectrum (i) typical PWM (ii) random PWM (Lai and Chen, 2013)	15
Figure 2.5	Spring-mass system model to represent the DVA theory (Zill et al., 2011)	18
Figure 2.6	Theoretical model of the panel for DVA attachment(Sun et al., 1996)	20
Figure 2.7	The cylindrical shell and the DVA attached to the shell (Huang and Fuller, 1998)	20
Figure 2.8	Tuned Mass Damper (TMD) on Lathe Machine (Yang et al., 2010)	22

Figure 2.9	DVA attached to the fuselage of turboprop aircraft. It is tuned by changing the weights (42) and also length of beam (40) (Van Joseph,1970)	23
Figure 2.10	Dynamic vibration absorber implemented on AC motor for angular velocity perturbation control (a) DVA (30) is attached to the AC motor (20) (b) The DVA consists of inertial mass (32), flexible spring (34) and mounting hub (36) (James et al., 1996)	24
Figure 2.11	Application of DVA for dishwasher machine electric motor (a) Electric motor (10) with DVA (1) used in dishwasher (12) (b) DVA (1) consists of beam (20) and mass (22) attached to the motor (10) (Vukorpa et al.,1997)	25
Figure 3.1	MarelliMotori induction motor (left) and Emerson SKA inverter (right)	28
Figure 3.2	Electrical wiring diagram of the motor-inverter pair (1-Induction Motor & 2-Inverter)	28
Figure 3.3	Experimental setup for PWM waveform tracing	30
Figure 3.4	Schematic of PWM Waveform tracing experimental setup (1-Induction Motor, 2-Inverter, 3-Active Differential Probe & 4-Digital Oscilloscope)	30
Figure 3.5	Experimental setup for spectral test	32
Figure 3.6	Schematic of spectral test (1-Induction motor, 2-Accelerometers, 3- Microphone, 4- LMS Scadas& 5-PC)	32
Figure 3.7	Surface vibration measurement grid	32
Figure 3.8	Experimental setup for experimental modal analysis (a) Excitation using impact hammer (b) Motor hung in “free-free” condition using rubber band	33

Figure 3.9	Schematic of motor structure impact test (1-Induction motor, 2-Accelerometer, 3-Impact Hammer, 4-Measurement points, 5-Rubber band, 6-LMS Scadas, 7-PC)	34
Figure 3.10	Measurement grid for modal analysis	34
Figure 3.11	Reference accelerometer attached to point 6 on motor housing while roving accelerometer currently at point 22 during ODS analysis	36
Figure 3.12	Schematic of operational deflection shape analysis (1-Induction motor, 2-Roving accelerometer, 3-Reference accelerometer, 4-Measurement points, 5-LMS Scadas, 6-PC)	36
Figure 3.13	A 20mm M6 bolt attached at point 55 on motor housing during impact test for modal analysis	37
Figure 3.14	Sample bolt lengths for impact test	38
Figure 3.15	Impact test on a 20 mm M6 bolt	39
Figure 3.16	Schematic of DVA impact test (1-induction motor, 2-DVA, 3-Impact Hammer, 4-Miniature Accelerometer, 5-LMS Scadas, 6-PC)	39
Figure 3.17	Experimental setup to see changes in motor structure local FRF upon final DVA attachment. Accelerometer is attached at position R1 at Location A and impact hammer is knocked at point 37	40
Figure 3.18	Schematic of Motor FRF validation experiment (1- Induction Motor, 2- DVA, 3- Impact hammer, 4- Miniature accelerometer, 5- Foam, 6-LMS Scadas, 7-PC)	41
Figure 3.19	Four different M6 threaded hole location on motor to attach DVA	42

Figure 3.20	(a) Location for surface vibration measurement. A 20mm DVA is attached and miniature accelerometer is attached at R1 (b) Illustration of various axes and their respective measurement points at Location A	42
Figure 3.21	Schematic of motor surface vibration measurement before and after DVA at location A, B, C and D. (1-Induction Motor, 2-DVA, 3-Accelerometer, 4-LMS Scadas, 5-PC)	43
Figure 3.22	Motor surface vibration and DVA vibration correlation measurement	44
Figure 3.23	Schematic of motor surface vibration and DVA vibration correlation measurement (1-Induction Motor, 2-DVA, 3,4-Accelerometer, 5-LMS Scadas, 6-PC)	44
Figure 3.24	Before and after DVA motor surface vibration and sound pressure level correlation measurement at location X1	45
Figure 3.25	Schematic of before and after DVA motor surface vibration and sound pressure level correlation measurement (1-Induction Motor, 2-DVA, 3-Microphone, 4-Accelerometer, 5-LMS Scadas, 6-PC)	45
Figure 3.26	Schematic for DVA effectiveness at variable speed measurement (1-Induction Motor, 2-DVA, 3-Accelerometer, 4-Inverter, 5-LMS Scadas, 6-PC)	46
Figure 3.27	Flowchart of methodology for research on application of DVA for induction motor electromagnetic noise suppression	47
Figure 4.1	Spectra comparison at 0 rpm	50
Figure 4.2	Spectra comparison at 250 rpm	51
Figure 4.3	Spectra comparison at 500 rpm	52

Figure 4.4	Spectra comparison at 750 rpm	53
Figure 4.5	Spectra comparison at 1000 rpm	54
Figure 4.6	Spectra comparison at 1250 rpm	56
Figure 4.7	Spectra comparison at 1500 rpm	57
Figure 4.8	(a) Frequency response function (b) phase angle of the motor structure	58
Figure 4.9	Mode 1 at 735 Hz indicates complex mode	60
Figure 4.10	Mode 3 at 2029 Hz indicates ovaling mode (Diametral Mode 2)	60
Figure 4.11	Mode 8 at 4534 Hz indicates wave mode (Diametral Mode 3)	60
Figure 4.12	Diametral mode of cylindrical structure (a) Ovaling mode (b) Wave mode (Gieras et al., 2005)	61
Figure 4.13	Sequence of ODS animation (from a to d) of motor structure at 6 kHz at speed of 0 rpm	62
Figure 4.14	Point 49 and 65 (marked in green circle) on the motor exhibits very high vibration displacement	63
Figure 4.15	Point 55 has threaded M6 hole for M6 DVA attachment	64
Figure 4.16	(a) Frequency response function (b) Phase angle for various lengths of sample bolts	65
Figure 4.17	PolyMAX stabilization diagram of 20 mm DVA	65
Figure 4.18	Surface vibration changes for 60mm bolt	67

Figure 4.19	Surface vibration changes for 20mm bolt	68
Figure 4.20	Surface vibration changes for 50mm bolt	68
Figure 4.21	(a) FRF changes at location R1 of point 55 on motor housing (b) Close range view of the FRF upon 20mm bolt attachment	70
Figure 4.22	Input-Transfer Function-Output concept for variable speed induction motor noise emission	71
Figure 4.23	Surface vibration spectrum at y-axis before and after DVA (a) at location Y1 (b) at location Y2	72
Figure 4.24	Surface vibration spectrum at z-axis before and after DVA (a) at location Z1 (b) at location Z2	72
Figure 4.25	Surface vibration spectrum at x-axis before and after DVA (a) at location X1 (b) at location X2	73
Figure 4.26	Surface vibration spectrum at r-axis before and after DVA (a) at location R1 (b) at location R2	74
Figure 4.27	Surface vibration reduction at (a) Z2 (b) X2 and (c) R2 at location C at 1000 rpm	76
Figure 4.28	Surface vibration reduction at (a) Z2 (b) X2 and (c) R2 at location D at 1000 rpm	77
Figure 4.29	Comparison of (a) decrease in surface vibration of motor and (b) increase in DVA vibration at location X1	78
Figure 4.30	Comparison of (a) decrease in surface vibration of motor and (b) increase in DVA vibration at location R1	79
Figure 4.31	Comparison of (a) decrease in surface vibration of motor and (b) increase in DVA vibration at location Z1	79

Figure 4.32	Reduction in (a) motor surface vibration and (b) sound pressure before and after DVA attachment at location X1	81
Figure 4.33	Reduction in (a) motor surface vibration and (b) sound pressure before and after DVA attachment at location X2	81
Figure 4.34	Reduction in (a) motor surface vibration and (b) sound pressure before and after DVA attachment at location R1	82
Figure 4.35	Surface vibration reduction at various speeds (a) 0 rpm (b) 250 rpm (c) 500 rpm	84
Figure 4.36	Surface vibration reduction at various speed (a) 750 rpm (b) 1000 rpm (c) 1250 rpm (d) 1500 rpm	85

LIST OF ABBREVIATIONS

AC	Alternating Current
AC-RPWM	Asymmetric Carrier Random PWM
EMA	Experimental Modal Analysis
FFT	Fast Fourier Transform
FRF	Frequency Response Function
IEC	International Electrotechnical Committee
ODS	Operational Deflection Shape
PFM	Pulse Frequency Modulation
PWM	Pulse Width Modulation
PZT	Piezoelectric Insert
RPPWM	Random Position Pulse Width Modulation
SLPWM	Slope Pulse Width Modulation
THD	Total Harmonic Distortion
TMD	Tunes Mass Damper
TVA	Tuned Vibration Absorber
UMP	Unbalanced Magnetic Pull

LIST OF SYMBOLS

B	Radial air gap magnetic flux density
E	Young's Modulus
F_1	Harmonic forcing force
F_R	Radial Maxwell magnetic force
F_T	Tangential magnetic force
g	Gravitational acceleration
I	Beam second moment of inertia
k_1	Stiffness of mass m_1
k_2	Stiffness of mass m_2
l	Length of beam
m	Mass of beam
m_1	Mass of primary structure
m_2	Mass of dynamic vibration absorber (DVA)
x_1	Displacement of primary structure
x_2	Displacement of DVA
X_1	Vibration amplitude of primary structure
X_2	Vibration amplitude of DVA
\ddot{x}_1	Acceleration of primary structure
\ddot{x}_2	Acceleration of DVA
μ_0	Air gap magnetic permeability
ω_n	Harmonic forcing force frequency
ω_1	Natural frequency of primary structure
ω_2	Natural frequency of DVA

PENGURANGAN HINGAR AKUSTIK ELEKTROMAGNETIK DARIPADA MOTOR INDUKSI KELAJUAN BOLEH UBAH DENGAN MENGGUNAKAN PENYERAP GETARAN DINAMIK

ABSTRAK

Hingar akustik elektromagnetik mempunyai ciri ton hingar yang dihasilkan oleh motor induksi kelajuan boleh ubah mewujudkan suasana yang tidak selesa kepada pengendali mesin. Hingar yang berlaku pada frekuensi tinggi ini kebiasaannya berlakupada gandaan frekuensi pensuisan pada pembalik. Penyelesaian masalah hingar ini pada umumnya dicapai dengan rekabentuk elektromekanikal dan modulasi lebar denyut untuk membasmi harmonik yang menyebabkan hingar. Penggunaan penyerap getaran dinamik adalah antara alternatif yang dikaji di dalam penyelidikan ini. Ujian spektrum menunjukkan bahawa daya tindakan elektromagnetik mempengaruhi secara langsung hingar elektromagnetik yang dihasilkan oleh motor induksi. Gandaan harmonik 3 kHz pada spektrum modulasi lebar denyut berlaku juga pada spektrum getaran permukaan dan spektrum hingar. Analisis mod dan ujian spektrum menunjukkan bahawa hingar dengan frekuensi 6 kHz pada kelajuan 1250 rpm dan ke bawah adalah disebabkan oleh getaran paksa. Pada halaju di atas 1250 rpm, hingar 3 kHz adalah disebabkan resonans. Bolt M6 sepanjang 20 mm digunakan sebagai penyerap getaran dinamik dan dipasang pada permukaan motor untuk mengurangkan hingar pada 6 kHz. Penyerap getaran dinamik menyerap getaran sebanyak 20% hingga 86% pada permukaan motor dan pengurangan aras tekanan bunyi sebanyak 12 dB(A) dapat dicapai. Ia juga berkesan pada lokasi lain pada motor dan juga pada semua kelajuan operasi. Penyerap getaran dinamik telah terbukti untuk mengurangkan hingar elektromagnetik daripada motor induksi kelajuan boleh ubah.

**ATTENUATION OF ELECTROMAGNETIC ACOUSTIC NOISE
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ABSTRACT

Tonal electromagnetic acoustic noise radiated from variable speed induction motor can be annoying to human operator. Occurring at high frequency, it often occurs at multiples of the inverter switching frequency. Solutions for the noise attenuation have been generally by means of electromechanical design and pulse width modulation (PWM) strategy to remove harmonics leading to noise generation. Dynamic vibration absorber (DVA) as an alternative solution was implemented in this research. Spectral test revealed that the input electromagnetic excitation has direct influence on the radiated electromagnetic acoustic noise from the induction motor. The multiples of 3 kHz harmonics in PWM spectrum was also present in the surface vibration and sound pressure spectrum. From experimental modal analysis and spectral test, it was found that the 6 kHz acoustic noise was due to forced vibration for speed of 1250 rpm and below. While at above 1250 rpm, the 3 kHz noise was due to resonance. A 20mm M6 bolt was used as DVA and attached to a point on the motor housing for targeted noise attenuation at 6 kHz. The DVA was able to absorb the surface vibration in the range of 20 to 86% and maximum sound pressure level reduction of 12 dB (A) was achieved. It was also effective at other locations on motor as well as at different operating speed. The DVA was thus proven to be a feasible method for electromagnetic noise attenuation in induction motor.

CHAPTER 1

INTRODUCTION

1.1 Overview

Induction motor is the most widely used motor for industrial applications (Sahay and Pathak, 2006). It is generally used to drive pumps, compressors, conveyor belts and fans. Apart from being low cost, its popularity is also due to its ruggedness and excellent reliability in various operating conditions. Figure 1.1 shows the construction of an induction motor. The main components of the induction motor that are responsible for torque generation are the cage rotor and stator.

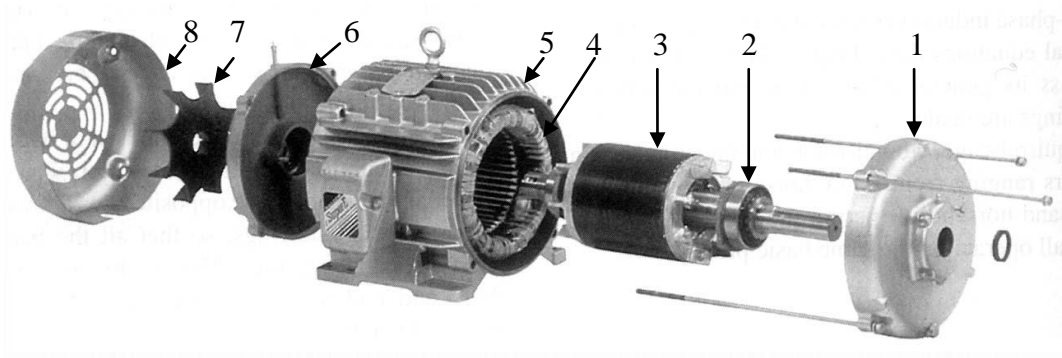


Figure 1.1 Exploded view of an induction motor. (1-Front end shield, 2 - Bearing, 3 – Cage rotor, 4 - Stator, 5 – Housing, 6 – Rear end shield 7- Cooling Fan, 8- Fan Cowl) (Wildi, 2002)

The induction motor produces its motion from the interaction of magnetic fields from both rotor and stator. Alternating current (AC) power supply to the stator coils produces rotating magnetic field around the stator. A second rotating magnetic field is then induced on the rotor bars of the squirrel cage. This two opposing magnetic field subsequently leads to the rotor's motion. Improving the advantage of the induction further for industrial use is the variable speed operation capability.

Using an inverter, the voltage and frequency of AC power supply can be controlled and thus a precise regulation of speed and torque is achieved.

While the induction motor is able to provide excellent motion drive, it has been known to produce acoustic noise which can be annoying to human exposure. The acoustic noise being emitted by an induction motor can be classified into three main categories: aerodynamic noise, mechanical noise and electromagnetic noise. Three different types of acoustic noise and its source are summarized in Table 1.1.

Table 1.1 Various types and source of acoustic noise from a variable speed induction motor (Gieras et al., 2005)

Type	Source	Noise Characteristics
Aerodynamic	Cooling fan airflow	Broadband
Mechanical	Ball bearing defects Bent shaft Rotor unbalance Shaft misalignment	Tonal
Electromagnetic	Electromagnetic force harmonics Phase unbalance Slotting effects Magnetic saturation Unbalanced magnetic pull	Tonal

All these three different types of noise source combines to produce overall sound pressure level emitted by the motor. In aerodynamic noise, air turbulence induced by the cooling fan interacts with the motor housing to create flow induced noise. With increasing motor speed, the aerodynamic noise also increases. Mechanical noise occurs at discrete frequencies and depends on the motor speed as well. Unlike the aerodynamic and mechanical noise, there are many sources that lead to the electromagnetic noise. These different sources lead to numerous harmonics in the air gap flux density between rotor and stator. This in turn leads to periodic

fluctuations radial magnetic forces which deforms the stator. The radial deformation is what leads to the electromagnetic acoustic noise (Gieras et al., 2005).

The electromagnetic noise emanating from inverter driven induction motor is generally a high frequency acoustic noise. This unpleasant high frequency noise is narrow band or tonal in nature. Unlike the broadband noise in which the acoustic spectrum is spread over a range of frequency, the tonal noise generally occurs at discrete frequencies. Psychoacoustics research has indicated that tonal acoustic noise is subjectively more annoying than broadband noise (Kryter, 1968). Typical electromagnetic acoustic noise from a variable speed induction motor occurs at frequencies from 1000 Hz to 20,000 Hz. These frequencies are generally multiples or harmonics of various design parameters of the induction motor such as inverter switching frequency, number of stator and rotor slots and line frequency. Although human hearing ranges from 200 Hz to 20,000 Hz, human ears are more sensitive to the frequency range between 1000 Hz and 5000Hz (May, 2000). Realizing the sensitivity at this region, narrow frequency bands of electromagnetic noise within and nearby this frequency range is to be avoided. Generally, the aerodynamic and mechanical noise will mask the electromagnetic noise. However in certain cases, the electromagnetic acoustic noise can be the most dominant source of noise. For example, electromagnetic acoustic noise is more perceivable in light rail vehicle with traction motor (Le Besnerais et al., 2009a). Thus, the solution for electromagnetic acoustic noise is crucial.

The research and development in electric motor noise abatement was largely driven by strict industrial regulations throughout the world. Realizing that acoustic noise is one of the occupational health hazard, the motor noise limit is regulated by International Electrotechnical Commission (IEC). Figure 1.2 shows the standards for

maximum permissible sound power levels for a IEC squirrel cage induction motor.

The noise limit is based on the rated power output and number of poles.

Rated speed n_N (rev/min)	$n_N \leq 960$			$960 < n_N \leq 1320$			$1320 < n_N \leq 1900$			$1900 < n_N \leq 2360$			$2360 < n_N \leq 3000$		
Methods of cooling	IC01	IC411	IC31	IC01	IC411	IC31	IC01	IC411	IC31	IC01	IC411	IC31	IC01	IC411	IC31
(simplified code) ^b	IC11	IC511	IC71W	IC11	IC511	IC71W	IC11	IC511	IC71W	IC11	IC511	IC71W	IC11	IC511	IC71W
	IC21	IC811	IC81W	IC21	IC811	IC81W	IC21	IC811	IC81W	IC21	IC811	IC81W	IC21	IC811	IC81W
	IC8A1W7			IC8A1W7			IC8A1W7			IC8A1W7			IC8A1W7		
	c	d	d	c	d	d	c	d	d	c	d	d	c	d	d
Rated output P_N (kW or kVA)	Maximum permissible sound power level L_{WA} (dB)														
$1 \leq P_N \leq 1.1$	73	73		76	76		77	78		79	81		81	84	
$1.1 < P_N \leq 2.2$	74	74		78	78		81	82		83	85		85	88	
$2.2 < P_N \leq 5.5$	77	78		81	82		85	86		86	90		89	93	

Figure 1.2 Maximum permissible Sound Power Levels in Decibels for IEC Squirrel

Cage Induction motors (Toliyat and Kliman, 2004)

Solutions for electromagnetic noise mitigation for variable speed induction motor can be generally divided into two main methods: electromechanical design and pulse width modulation (PWM) strategy. The electromechanical design solution looks into the various geometrical design parameters of the induction motor. Examples include rotor-stator slot number combination (Kobayashi et al., 1997), stator slot opening width (Le Besnerais., 2009b) and rotor skew angle (Nau, 1997). This parameter has to be taken into account at the early stage of the design before manufacturing the motor. In PWM strategy, the PWM waveform from the inverter is optimized such that time harmonics of the magnetic flux density is minimized (Timar and Lai, 1994). Examples include ultrasonic switching (Gilliam et al., 1988), random PWM (Habetler and Divan, 1991) and pulse frequency modulation (PFM) (Ertan and Simsir, 2004).

Structural modification as a method to attenuate annoying acoustic noise has a potential to reduce the electromagnetic noise as well. In structural modifications, the vibration response of the structure can be altered by shifting the resonance or

changing the dynamic performance parameters. Various methods for structural modifications include mass modifications, selection of materials, stiffness alteration and vibration absorber addition (Kundra and Nakra, 1997). Structural modification as means to mitigate noise has been investigated for gearbox housing noise (Inoue et al., 2002) and drum brake squeal (Hamid et al., 2013).

In this research, the use of dynamic vibration absorber (DVA) to attenuate electromagnetic noise is investigated. DVA is a passive vibration control method whereby a secondary mass attached to a troublesome primary mass. The secondary mass natural frequency needs to be similar to the frequency of force excitation in order for primary mass vibration reduction (Mehta, 2012). The reduction should lead to reduction of the noise as well. DVA application has been popularly used for vibration control and the only reported use for acoustics control has been for aircraft cabin noise (von Flotow, 2000). It has not been reported to be used for noise control of electric motor and it is thus worth investigating on an induction motor in this research.

1.2 Problem Statement

Solutions for electromagnetic noise for induction motor have been largely focused on electromechanical design and PWM strategy. Various possibilities to optimize this two methods have reached its limit due to a range of tradeoffs such as sacrificing electrical efficiency and manufacturing costs. Moreover, there is a limit to the maximum noise level reduction achievable by each method. DVA as an alternative means to mitigate the electromagnetic acoustic noise is thus evaluated.

1.3 Motivation

Due to the electrical nature of the electromagnetic noise generation, the solution for electromagnetic noise has been tackled from electrical engineering point

of view. The current solutions available revolve around controlling the source of harmonics in the magnetic field between rotor and stator. From mechanical engineering standpoint, the electromagnetic noise problem can be solved by applying the solution at the receiver end by attaching a DVA on the motor to absorb and reduce the surface vibration that leads to acoustic noise. This research work is thus motivated by the need to solve the problem in an alternative way.

1.4 Objective

The main objective of this research is to evaluate the effectiveness of DVA to suppress tonal electromagnetic acoustic noise from variable speed induction motor

1.5 Contributions

The first contribution of this research is to investigate the correlation between the input electromagnetic excitation and the radiated electromagnetic acoustic noise. Though literature had mentioned that the frequency content of PWM has influence on the acoustic noise, but there is no available experimental data to show clearly the causal relationship. Through various noise and vibration characterization, this research thus shows the causal relationship between the input electromagnetic excitation and output electromagnetic acoustic noise.

The second and most important contribution is the investigation into the feasibility of DVA to suppress electromagnetic acoustic noise. The precedence of electromechanical design and PWM strategy has narrowed the scope for electromagnetic acoustic noise solution by various researchers. This research thus investigated an alternative solution.

1.6 Scope

The research is limited to experiments on motor noise and vibration characterization and DVA implementation. Basic noise and vibration characterization experiments such as spectral test, modal analysis and ODS was performed. PWM waveform tracing to determine the frequency content of electromagnetic excitation was conducted. Prior to DVA implementation, modal analysis on candidate DVA was carried out to obtain the suitable DVA. During implementation, effectiveness of DVA at various location, axis and speed was investigated.

1.7 Outline

This thesis is divided into five chapters which are introduction, literature review, methodology, results and discussions and conclusions. Chapter one presents basic idea of this research. A brief introduction to induction motor and electromagnetic noise is introduced. Problem statements, motivation, objectives, contributions, scope and outline are stated. Chapter two examines further into the literature on the electromagnetic noise generation mechanism and various solutions for noise suppression method. This chapter also presents the theory of DVA. Chapter three reports the methodology for various experiments for noise and vibration characterization and also implementation of DVA on the motor structure. In chapter four, results from the characterization and DVA implementation is presented. Finally, chapter five concludes all the findings from this research.